Accelerator Physics Issues at LHC & Beyond
Part II

Frank Zimmermann, CERN, SL/AP

(A) Past and Future

(B) The Large Hadron Collider (LHC)
   - parameters, magnets, beam-beam effects, pre-injectors, ion collisions,...
   - A new phenomenon: Electron Cloud (today)

(C) LHC Upgrades, VLHC-I and II (today)
Electron Cloud

Observed with the LHC beam:
1999 SPS, 2000 PS, 2000 PS-SPS transfer line

primary $e^-$—generated by photoemission or gas ionization; their number amplifies along a bunch train due to beam-induced multipacting

(1) Build Up, Saturation, Decay

(2) Wake Fields and Instabilities

(3) Heat Load

(4) LHC Approach
Intensity of 72-bunch LHC beam in SPS vs. time. Batch intensity (top) and bunch intensity for the first 4 bunches and last 4 bunches (where losses are visible after about 5 ms) of the batch (bottom). (Courtesy G. Arduini, 2001).
Build Up, Saturation, Decay

$e^-$ production mechanisms:

- residual gas ionization;
  typical rate $d^2\lambda_e/(ds\,dt) \approx 5 \times 10^{11} \, e^- \, m^{-1} s^{-1}$

- synchrotron radiation and photo-emission;
  typical rate $d^2\lambda_e/(ds\,dt) \approx 5 \times 10^{18} \, e^- \, m^{-1} s^{-1}$

- secondary emission: (1) true secondaries &
  (2) elastically reflected or rediffused; \( \rightarrow \)
  exponential growth
Normalized secondary electron energy distribution for conditioned copper, revealing three components: true secondaries ($E \ll E_p$), elastically scattered ($E \approx E_p$) and rediffused (in between). [N. Hilleret, 2001]
Secondary emission yield for perpendicular incidence vs. primary electron energy with and w/o elastically scattered electrons. Parametrization based on measurements for LHC prototype chamber. [Ian Collins, 2000]
Schematic of electron-cloud build up in the LHC beam pipe. [Courtesy Francesco Ruggiero]

Proper multipacting: $n_{\text{min}} \equiv \frac{h_y^2}{N_b r_e L_{\text{sep}}} = 1$
<table>
<thead>
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<th>PEP-II</th>
<th>KEKB</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
<th>PSR</th>
<th>SNS</th>
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<td>e⁺</td>
<td>e⁺</td>
<td>p</td>
<td>p</td>
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<td>10</td>
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<td>50</td>
<td>100</td>
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<td>ch. $\frac{1}{2}$ size $h_y$ [mm]</td>
<td>25</td>
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<td>0.24</td>
<td>0.15</td>
<td>0.0002</td>
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F. Zimmermann  
Accelerator Physics Issues at the LHC and Beyond
Simulation of Cloud Build Up (Schematic)

- beam image
- electron image
- primary (photo-)electrons
- secondary electrons
- slices
- bunches
indicators of $e^-$ build up

(1) nonlinear pressure rise $\rightarrow \rho_e$

(2) pick ups or dedicated $e^-$ monitors $\rightarrow \rho_e$

(3) tune shift along the train $\rightarrow \rho_e$

(4) beam-size blow up along the train

(5) luminosity drop
example: magnitude of $e^-$ cloud in the SPS (1) from pressure rise [O. Gröbner]: pressure balance reads $S_{\text{eff}} P/(k_B T) = Q$, where $S_{\text{eff}}$ pumping speed in volume per meter per second, $Q = \alpha d\dot{\lambda}_e / ds$ total flux of molecules per unit length ($\alpha$: desorption yield per electron) and $P = k_B T N/V$.

$$\frac{d\lambda_e}{ds} = \frac{T_{\text{rev}}}{\alpha k_B T} S_{\text{eff}} P$$

With $P = 100$ nTorr, $\alpha \approx 0.1$ and $S_{\text{eff}} \approx 20$ l s$^{-1}$ m$^{-1}$:

$$\frac{d\lambda_e}{ds} \approx 10^{10} \text{electrons \over bunch - train meter}$$
(2) from damper pick-up measurements [W. Hoefle]:
a few $10^8$ electrons per bunch passage are deposited on the pick-up; this amounts to $10^9 - 10^{10}$ per train, or, with an effective pick-up length of about 10 cm,

$$\frac{d\lambda_e}{ds} \approx 10^{10} \frac{\text{electrons}}{\text{bunch} - \text{train meter}}$$

The two estimates are consistent.
Sum and **difference signal** on damper pick-up during the passage of an LHC batch in the SPS (1μs/div). (Courtesy W. Hofle, 2001).
Simulated electron-cloud build up for an SPS dipole chamber, with and without elastic electron reflection. Saturation at

\[ \lambda_{e,\text{sat}} \sim \frac{N_b}{L_{\text{sep}}} \approx 1.3 \times 10^{10} \, \text{m}^{-1} \rightarrow \text{‘neutralization’ density} \]

\[ \rho_{\text{sat}} \approx \frac{N_b}{(\pi h_x h_y L_{\text{sep}})} \approx 3 \times 10^{12} \, \text{m}^{-3}. \]
Fourier spectrum of the vertical oscillations of the LHC-beam bunch centroids as a function of bunch number
Wake Fields and Instability due to Electron Cloud

- Multi-Bunch Instability
- Coherent and Incoherent Tune Shift, etc.
- Single-Bunch Instability
  strong head-tail (TMCI), regular head-tail, transverse & longitudinal wakes, potential-well distortion
Snapshots of the horizontal and vertical electron phase space (top) and their projections onto the position axes (bottom). (Courtesy G. Rumolo, 2001).
adiabatic trapping (B. Richter, SLAC, March 2000)

WKB approximation $\rightarrow$ adiabaticity condition

$$A \equiv \sigma_z \omega_{e,y} \sqrt{8e/c} \gg 1$$

where $e = 2.718 \ldots$

$A \approx 10$ for KEKB, PEP-II, PS, SPS, LHC!
Simulated bunch shape after 0, 250 and 500 turns (centroid and rms beam size shown) in the CERN SPS with an $e^-$ cloud density of $\rho_e = 10^{12} \text{ m}^{-3}$, without (left) and with (right) proton space charge (Courtesy G. Rumolo).
 Beam size evolution for an SPS bunch interacting with an electron cloud as predicted by different simulation approaches. (Courtesy G. Rumolo, 2001).
Wake force $W_1$ induced by an electron cloud; each line represents a different cloud size. **Left:** KEKB; right: SPS. [K. Ohmi et al., HEACC’01]. (Courtesy K. Ohmi, 2001).
Wake force in V/m/C computed by displacing slice 1 and 40 (out of 100) of a Gaussian bunch (Courtesy G. Rumolo, 2001).
TMCI calculation: betatron side band frequencies
\((\omega - \omega_\beta)/\omega_s\) vs. \(cR_s/Q \propto \rho_e\) for KEKB LER. [K. Ohmi et al., HEACC’01]. (Courtesy K. Ohmi, 2001).
estimated TMCI thresholds

<table>
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<tr>
<th>accelerator</th>
<th>PEP-II</th>
<th>KEKB</th>
<th>PS</th>
<th>SPS</th>
<th>LHC</th>
<th>PSR</th>
<th>SNS</th>
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<td>e⁻ osc./bunch</td>
<td>0.8</td>
<td>1.0</td>
<td>1</td>
<td>0.75</td>
<td>3</td>
<td>34</td>
<td>970</td>
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<tr>
<td>$n_{osc} \equiv \omega_e \sigma_z / (\pi c)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TMCI threshold</td>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>0.25</td>
<td>3</td>
<td>(0.6)</td>
<td>(0.5)</td>
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<td>$\rho_e$ [$10^{12}$ m$^{-3}$]</td>
<td></td>
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<td>density ratio</td>
<td>19</td>
<td>4</td>
<td>0.35</td>
<td>11</td>
<td>4</td>
<td>(92)</td>
<td>(27)</td>
</tr>
<tr>
<td>$\rho_{e,\text{sat}} / \rho_{e,\text{thresh}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Detail of the sum (top) and delta (bottom) signals at the SPS provided by the wide-band transverse pick-up in the vertical plane. *Head-tail motion inside the bunches is visible.* (Courtesy G. Arduini, 2001). Wake period determined from measured head-tail motion: $\lambda_{e^-,\text{wake}} \approx \sigma_z$! (K. Cornelis).
Simulated centroid motion and vertical beam size with zero and positive chromaticity in the SPS ($\xi_y = 0.2$). Machine broadband impedance is also included. (Courtesy G. Rumolo, 2001).
Energy distribution of $e^-$s incident on LHC chamber wall for a chamber radius $r = 158$ mm (left) and 29 mm (right) (G. Rumolo).
Snapshot of transverse $e^-$ distribution in an LHC dipole chamber (F.Z., 1997). Parameters: $\delta_{\text{max}} = 1.3$, $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$. 
Average arc heat load and cooling capacity as a function of bunch population $N_b$, for various $\delta_{\text{max}}$. Other parameters are $\epsilon_{\text{max}} = 240$ eV, $R = 5\%$, $Y = 5\%$, and elastic electron reflection is included.
LHC Recipe

- in arc dipoles: use sawtooth chamber to reduce photon reflections
- coat all warm sections with getter material TiZr (low secondary emission yield)
- rely on surface scrubbing during the commissioning to reduce the maximum secondary emission yield to a value of 1.1
Sawtooth chamber prototype; the sawtooth reduces the photon reflectivity $R$ to 1.3% [co-laminated Cu: $R \approx 80$%]. (Ian Collins).
Comparison of dose dependence of the Secondary Emission Yield as measured at CERN and SLAC (N. Hilleret et al., 2001).
Newly Installed SPS $e^-$ Cloud Detectors

- **Pick-ups** for $e^-$ characteristics
  - $e^-$ cloud build up, $e^-$ energy distribution, triggering on the batch

- **Behavior of $e^-$** in a dipole magnetic field
  - ‘strip detector’
  - ‘triangle detector’

- **Scrubbing effect** by *in-situ* measurement of secondary emission yield

- **Ion detectors** to exclude ion-stimulated desorption

- **WAM_PAC Cu calorimeter** to directly measure heat load from $e^{-1}$ cloud
Cu Calorimeter
WAMPAC in BA4

SSWG 17/7/2001
#1 Calibration: $Q = 5$ W

$$\frac{\Delta T}{\Delta t} = \frac{Q}{m \, C_p} = 0.25 \text{ K/min}$$

- TC1
- TC2 = 0.2501
- TC3 = 0.0958
- TC4
- TC5 = 0.2004
- TC6
Triangle detector
Per age de la chambre en face du détecteur

couverture des trous 50 x 300

chambre MBA
position SPS 518

chambre MBA

BNC

détecteur \textsuperscript{\texttrademark} triangles

détecteur \textsuperscript{\texttrademark} bandes

connecteur 25 broches
ceramaseal DB25

champ magnétique

JM-L\_ 10 avril 2001
Strip detector

SPS Machine as a vacuum test bench for the electron cloud studies with LHC type beams
Stripe signal for 8.5 mm orbit bump with 2 s duration. The stripe clearly follows the beam. (G. Arduini, et al., 2001).
Threshold of the e⁻ cloud in a dipole field

Limit of detection: $4.2 \times 10^{-7} \ A/m^2$

Magnetic field: 2000 Gauss

Electron-stripe intensity in a 2-T dipole field vs. bunch population. Threshold at $2 \times 10^{10}$ protons per bunch.
e⁻ cloud behaviour in a dipole magnetic field - Magnetic field passing through 0 Gauss

e⁻ stripe vs. magnetic field; signal disappears for $|B| \leq 15$ G.
At higher intensity $N_b \approx 6 \times 10^{10}$ two stripes are observed! Spacing consistent with simulation.
(C) *Beyond LHC: LHC-II and VLHC*

- higher luminosity and/or energy
- more bunches?
- crossing angle & crabbing
- magnets (stronger and/or cheaper)
- synchrotron radiation
- emittance control
- collective effects & electron cloud
- IP debris, quench limits, & safe beam abort
- quasi-continuous beams?
Luminosity for Bunched Beams

\[ L = \frac{N_b^2 f_{\text{rep}} H_D}{4\pi \sigma_x \sigma_y} \eta_L \]

For a horizontal crossing, \( \eta_L \) is

\[ \eta_L = \frac{2}{\sigma_z \sqrt{\pi}} \int_0^\infty \exp \left( -\left( \frac{z}{\sigma_z} \right)^2 \left\{ 1 + \frac{\theta_c^2}{4 \theta_d^2} \left[ \frac{1}{1 + (z/\beta_x^*)^2} \right]^2 \right\} \right) \sqrt{\frac{1 + (z/\beta_x^*)^2}{(1 + (z/\beta_y^*)^2)}} \]

where \( \theta_d = \sigma_x/\sigma_z \), \( \theta_c \) the full crossing angle.
Beam-Beam Tune Shifts for Bunched Beams

Assuming $\beta_x^* \approx \beta_y^*$ and $\epsilon_x \approx \epsilon_y$ the beam-beam tune shifts for a particle at the center of the bunch are

\[
\Delta Q_x = -\frac{N_b r_p}{2\pi \gamma} \frac{1}{\sqrt{2\pi} \sigma_z} \int_\infty \left( \beta^* + \frac{s^2}{\beta^*} \right) \left[ \left( \frac{1}{(\beta^* + s^2/\beta^*) \epsilon} + \frac{1}{\theta_c^2 s^2} \right) \right. \\
\left. \exp \left( -\frac{\theta_c^2 s^2}{2 (\beta^* + s^2/\beta^*) \epsilon} \right) - \frac{1}{\theta_c^2 s^2} \right] \exp \left( -\frac{s^2}{2 \sigma_z^2} \right) \, ds
\]

\[
\Delta Q_y = -\frac{N_b r_p}{2\pi \gamma} \frac{1}{\sqrt{2\pi} \sigma_z} \int_\infty \left( \beta^* + \frac{s^2}{\beta^*} \right) \left[ \frac{1}{\theta_c^2 s^2} \left( 1 - \exp \left( -\frac{\theta_c^2 s^2}{2 (\beta^* + s^2/\beta^*) \epsilon} \right) \right) \right] \exp \left( -\frac{s^2}{2 \sigma_z^2} \right) \, ds ,
\]
Luminosity (left) and total beam-beam tune shift (right) vs. crossing angle; parameters: \( N_b = 1.7 \times 10^{11}, \beta^* = 0.25 \text{ m}, \sigma_z = 7.7 \text{ cm}, n_b = 2800, \gamma \epsilon_\perp = 3.75 \mu\text{m}. \)
Applying a deflection of opposite sign to the head and tail of each bunch, luminosity loss due to the crossing angle is avoided.
Crab Cavities cont’d

Distance between last quadrupole and IP about 20 m. Outer quadrupole radius 25 cm. Two separate final quadrupoles require $\theta_c \geq 25$ mrad. Transverse crab deflecting voltage:

$$V_\perp = \frac{cE \tan \theta_x/2}{e\omega_{rf} \sqrt{\beta^*_x/\beta_{crab}}}$$

<table>
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<tr>
<th>variable</th>
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<th>KEKB (GeV)</th>
<th>HER (GeV)</th>
<th>LHC (TeV)</th>
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<td>7.0</td>
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<td>RF frequency</td>
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<td>1.3 GHz</td>
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<td>half crossing angle</td>
<td>$\theta_c/2$</td>
<td>11 mrad</td>
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<td>IP beta function</td>
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<td>100 m</td>
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<td>required kick voltage</td>
<td>$V_\perp$</td>
<td>1.44 MV</td>
<td>144 MV</td>
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phase diagram of Nb$_3$Sn

- Temperature (K)
- Current density (A/cm$^2$)
- Magnetic field (T)
- Nb$_3$Sn
- Nb-Ti

Critical J-H-T surface

Axial strain on wires

- 12 T
- 14 T
- 16 T

$\varepsilon = 0$ after cool-down to 4.2 K
Stronger Magnets? *$Nb_3Sn$* instead of *$NbTi$*

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<th>Group</th>
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<td>1982</td>
<td>CERN</td>
<td>quad</td>
<td>71 T/m</td>
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<tr>
<td>1983</td>
<td>CERN/Saclay</td>
<td>dipole</td>
<td>5.3 T</td>
</tr>
<tr>
<td>1985</td>
<td>LBL</td>
<td>dipole D10</td>
<td>8 T</td>
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<td>KEK</td>
<td>dipole</td>
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<td>BNL</td>
<td>dipole</td>
<td>7.6 T</td>
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<td>1991</td>
<td>CERN-ELIN</td>
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<td>dipole MSUT</td>
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<td>2001</td>
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## LHC-II Parameters

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<th>LHC-II</th>
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<td>dipole field $B$ [T]</td>
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<td>total energy/beam [MJ]</td>
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<td>number of bunches $n_b$</td>
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<td>bunch population $N_b$ [$10^{11}$]</td>
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<td>1.05</td>
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<tr>
<td>rms IP beam size $\sigma_{x,y}^*$ [\mu m]</td>
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<tr>
<td>rms IP div. $\sigma_{x',y'}^*$ [\mu rad]</td>
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<td>IP beta $\beta_{x,y}^*$ [m]</td>
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<td>beam-beam tune shift / IP $\xi_{x,y}$</td>
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<td>0.005</td>
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<tr>
<td>crossing angle $\theta_c$ [\mu rad]</td>
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<td>rms bunch length $\sigma_z$ [cm]</td>
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## LHC-II Parameters (cont’d)

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<th>Value 2</th>
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<td>bunch spacing $L_{sep}$ [m]</td>
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<td>SR power $P_{SR}$ [kW]</td>
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<td>114</td>
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<tr>
<td>SR dipole heat load $dP/ds$ [W/m]</td>
<td>0.2</td>
<td>6.6</td>
</tr>
<tr>
<td>rms transv. emittance $\gamma\epsilon_{x,y}$ [$\mu$m]</td>
<td>3.75</td>
<td>3.75 → 1.0</td>
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<tr>
<td>eq. horiz. emittance $\gamma\epsilon^e_{x}$ [$\mu$m]</td>
<td>2.03*</td>
<td>1.07*</td>
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<tr>
<td>longit. emittance $\epsilon_L (\sigma)$ [eVs]</td>
<td>0.2</td>
<td>0.15*</td>
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<tr>
<td>damp. time $\tau_{x,SR}$ [hr]</td>
<td>52</td>
<td>6.5</td>
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<td>IBS growth time $\tau_{x,IBS}$ [hr]</td>
<td>142</td>
<td>345 (in.)</td>
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<td>events per crossing</td>
<td>18</td>
<td>90</td>
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<tr>
<td>peak luminosity $L$ [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>10.</td>
</tr>
<tr>
<td>lum. lifetime $\tau$ [hr]</td>
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<td>3.2</td>
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Emittance Evolution

synchrotron radiation amplitude damping time

\[ \tau_z J_z = \left( \frac{3 (m_p c^2)^3}{e^2 c^3 r_p Z^2} \right) \frac{1}{B^2 E} \left( \frac{C}{2\pi \rho} \right) \approx \frac{16644 \text{hr}}{E[\text{TeV}] B[\text{T}]^2} \left( \frac{C}{2\pi \rho} \right) \frac{A^4}{Z^4} \]

damping decrement (for 2 IPs)

\[ \delta = \frac{T_0}{n_{\text{IP}} \tau_{x,y}} \approx 5.7 \times 10^{-13} \ E[\text{TeV}]^2 B[\text{T}] \frac{Z^3}{A^4} \]

does this affect the maximum beam-beam tune shift?

maximum \( \xi \): measurements and simulations fitted by

\[ \xi_{\text{max}} \propto 0.009 + 0.021 \left( \frac{\delta}{10^{-4}} \right)^{0.5} \]

Tune shift parameter vs. damping decrement. [LEP data courtesy of R. Assmann; not beam-beam limited]
more important consequence of synchrotron radiation: shrinkage of emittance during the store situation different from $e^-$ storage rings; $\tau_{\text{SR}} \sim$ hours

SR equilibrium emittance:

$$\epsilon_{x,N}^{\text{SR}} \approx \frac{55}{32\sqrt{3}} \frac{\lambda_A}{J_x} \left( \frac{\gamma^3}{Q_\beta^3} \right) \left( \frac{C}{2\pi \rho} \right)^3$$

for LHC-II and HF VLHC 2–3 orders of magnitude below desired design emittance!

→ large beam-beam tune shifts, halo, background,...?

(J. Gareyte)
equilibrium emittance determined by balance of radiation damping and intrabeam scattering

\[
\frac{1}{\tau_{x,\text{IBS}}} \approx \frac{cr_p^2 N_b L_c}{16 Q \epsilon_{x,N}^2 \sqrt{\kappa} \sqrt{\kappa + 1} \gamma \sigma_z \sigma_\delta}\text{ [J. Wei]}
\]

where \( L_c \approx 20 \). Asymptotically, for \( \gamma \gg Q_\beta \):

\[
1/\tau_{\delta,\text{IBS}} \approx 1/\tau_{x,\text{IBS}} \text{ and } \sigma_\delta \approx Q_\beta^{3/2} \sqrt{\epsilon_x/\rho}
\]

**IBS equilibrium emittance:**

\[
\epsilon_{x,N}^{\text{IBS}} = \frac{\rho^{5/6} N_b^{1/3}}{Q_\beta \gamma^{7/6}} \left( \frac{Z f_{\text{rf}} eV_{\text{rf}}}{cE \kappa (\kappa + 1)} \right)^{1/6} \left( \frac{C}{2\pi \rho} \right)^{1/6} \left( \frac{3r_p L_c}{16} \right)^{1/3}
\]

\( f_{\text{rf}} \): rf frequency; \( V_{\text{rf}} \): total rf voltage

\( \epsilon_y = \kappa \epsilon_x \) due to coupling and spurious \( D \);

assume \( \kappa = 1 \) for LHC-II
Evolution of **transverse emittance** vs. time in LHC-II.
Evolution of **beam current** during a store in LHC-II.
Evolution of beam-beam tune shift vs. time in LHC-II.
Evolution of **luminosity** during a store in LHC-II.
Collective Effects

- loss of Landau damping for higher-order longitudinal modes (F. Ruggiero, J. Rogers):
  \[
  \sigma_s \geq \frac{C}{2\pi} \left[ \frac{\pi^3 N_b f_{rev} e}{6 \ h_{rf}^3 V_{rf} \ \text{Im} \left( \frac{Z_L}{n} \right)_{\text{eff}}} \right]^{1/5}
  \]

- longitudinal microwave instability

- transverse coupled-bunch resistive-wall instability

- electron cloud
Evolution of **rms bunch length** during a store in LHC-II, and instability thresholds for $\text{Im}(Z_L/n)_{\text{eff}} \approx 0.1 \ \Omega$ (LHC).
Evolution of **rms bunch length** during a store in LHC-II, when after 3 hours **noise** maintains $\epsilon_L \geq 0.104$ eVs.
Total Beam Current

synchrotron radiation power

\[ P_{SR} = \frac{C \gamma E^4 N_b n_b c}{C \rho} = U_0 f_{rev} n_b N_b \]

using \( L \) and \( \xi \) this can be rewritten as

\[ P_{SR} = \left( \frac{8 \pi r_p^{3/2}}{\sqrt{3 c E_A}} \right) \frac{\kappa}{1 + \kappa^2} \frac{E^{3/2} L \beta_x^*}{\xi \sqrt{J_z \tau_z}} \sqrt{\frac{C}{2 \pi \rho}} \]

scaling:

\( B = \text{constant} \rightarrow J_z \tau_z \propto 1/E \) and \( P_{SR} \propto E^2 L \)
\( B \propto E^{1/2} \rightarrow J_z \tau_z \propto 1/E^2 \) and \( P_{SR} \propto E^{5/2} L \).
Wall plug power density vs. SR load for different solutions: cold BS, warm BS/shield & photon stop (P. Bauer et al.).
Sketch of the proposed VLHC-II photon stop (P. Bauer et al., PAC2001).
Average arc heat load as a function of bunch population for bunch spacings of 12.5 ns, 15 ns, and 25 ns, and a maximum secondary emission yield $\delta_{\text{max}} = 1.1$. Elastically reflected electrons are included.
Average arc heat load as a function of bunch spacing, for $\delta_{\text{max}} = 1.1$ and various bunch populations.
www.vlhc.org
Design Study for a Staged Very Large Hadron Collider
Transmission Line Magnet

- 2-in-1 warm iron
- Superferric: 2T bend field
- 100kA Transmission Line
- Alternating gradient (no quadrupoles needed)
- 65m Length
- Self-contained including Cryogenic System and Electronics Cabling
- Warm Vacuum System
Operating Margin Verified

Seven Designs Tested

-~0.8K margin at design current of 87.5 kA
-~25kA margin at nominal peak temperature of 6.0 K

(similar margins for three variants used in Design Report)
VLHC DESIGN STUDY SITE LAYOUT

- Clockwise Beam Extraction Line
- Counter-Clockwise Beam Extraction Line
- Beam Crossover, Power & Cryo Feed
- Transfer Line for Counter-Clockwise Injection (3 km Ramp)
- Transfer Line for Clockwise Injection (3 km Ramp)
- Det A
- Det B
- RF
- Utility Straight Section
- Tevatron (Bipolar)
- Magnet Factory
- X (meters)
- Y (meters) (NOT TO SCALE)

- Beam Stop
- Stage 2 Bypass
- Snowmass

July 2, 2001

P. Limon
‘Continous Beams’ or Super Bunches

- ISR was extremely successful
- continuous beams abandoned due to scarcity of antiprotons, no longer a problem
- no PACMAN bunches!
- no electron cloud!
- use induction acceleration modules, 25 kV/m, to generate long bunches bounded by barrier buckets (K. Takayama)
- stochastic cooling
- higher current
- route to high luminosity

exciting new development
Schematic of Super Bunches in a High-Luminosity Collider (K. Takayama et al.)
Continuous Beams – Luminosity

\[ L = \frac{c\lambda_1\lambda_2 l_{\text{det}}}{4\pi\sigma_0^2} K \left( \frac{l}{2\beta^*}, \frac{\beta^*\theta_c}{\sigma_0} \right) \]

where

\[ K(\xi, \eta) = \frac{1}{\xi} \int_{-\xi}^{\xi} \frac{1}{1 + u^2} \exp \left[ -\frac{\eta^2}{4} \frac{u^2}{1 + u^2} \right] du \]

The integral \( K(\xi, \eta) \) is defined such that \( K(\xi, \eta) \to 2 \) for \( \xi, \eta \to 0 \) (E. Keil, et al., 1972/73).
Continuous Beams – Tune Shift

For horizontal crossing, the beam-beam tune shifts are

\[
\Delta Q_x = \frac{2 \lambda r_p l}{4 \pi \gamma \epsilon_\perp} I_x \left( \frac{l}{2 \beta^*}, \frac{\beta^* \theta_c}{\sigma_0} \right)
\]

\[
\Delta Q_y = \frac{2 \lambda r_p l}{4 \pi \gamma \epsilon_\perp} I_y \left( \frac{l}{2 \beta^*}, \frac{\beta^* \theta_c}{\sigma_0} \right)
\]

where

\[
I_x(\xi, \eta) = \frac{1}{\xi \eta^2} \int_{-\xi}^{+\xi} (1 + u^2) \left[ \left( u^{-2} + \frac{\eta^2}{1 + u^2} \right) \exp \left( -\frac{\eta^2}{2} \frac{u^2}{1 + u^2} \right) - u^{-2} \right] \, du
\]

\[
I_y(\xi, \eta) = \frac{1}{\xi \eta^2} \int_{-\xi}^{+\xi} (1 + u^{-2}) \left[ 1 - \exp \left( -\frac{\eta^2}{2} \frac{u^2}{1 + u^2} \right) \right] \, du
\]

and the interaction happens between \(-l/2\) and \(l/2\). The integrals \(I_{x,y}(\xi, \eta)\) are defined such that \(I_{x,y}(\xi, \eta) \to 1\) for \(\eta \to 0\) and all \(\xi\).
Luminosity (left) and beam-beam tune shifts (right) as a function of crossing angle, for a continuous beam with a line density \( \lambda = 8.8 \times 10^{11} \text{ m}^{-1} \) (40 A current), \( \beta^* = 0.25 \text{ m} \), \( l_{\text{det}} = 1 \text{ m} \), \( l = 20 \text{ m} \), and \( \gamma \epsilon_\perp = 3.75 \mu \text{m} \).
Optimization of Continuous Beam Parameters – Length & Number & Charge of Super-Bunches?
Ongoing Study at CERN

- maximum luminosity
- maximum beam-beam tune shift
- acceptable heat load
- timing constraints by (induction) rf system
- injectors and filling time
- beam abort system
Conclusions

- hadron colliders have performed exceedingly well in the past

- the LHC will break new territory:
  - highest energy (14 TeV) and highest luminosity \(10^{35} \text{ cm}^{-2}\text{s}^{-1}\) ever
  - long-range collisions
  - strong-strong collisions
  - electron cloud
– radiation damping stronger than IBS
- beyond LHC: LHC upgrades and various stages of VLHC, Eloisatron, ...
– higher fields or larger circumference (→ peculiar collective effects)
– more synchrotron radiation; possibly more electron cloud
– new exciting development: ‘quasi-continuous beams’ (closing the circle to the ISR)
Thanks

Web addresses

- LHC http://lhc.web.cern.ch/lhc/
- LHC beam-beam effects
  http://wwwslap.cern.ch/collective/zwe/lhcbb/Welcome.html
- LHC electron cloud http://wwwslap.cern.ch/collective/electron-cloud/electron-cloud.html
- Accelerator Physics Group of the CERN SL (SPC+LHC) Division http://wwwslap.cern.ch/
- VLHC http://vlhc.org/
## Extended Parameter Set for pp or p\bar{p} Colliders

<table>
<thead>
<tr>
<th>acc.</th>
<th>Sp\bar{p}S</th>
<th>TeV2a</th>
<th>LHC</th>
<th>LHC-II</th>
<th>VLHC-I</th>
<th>VLHC-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ [TeV]</td>
<td>0.32</td>
<td>0.98</td>
<td>7</td>
<td>14</td>
<td>20</td>
<td>87.5</td>
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<tr>
<td>$B$ [T]</td>
<td>1.4</td>
<td>4.34</td>
<td>8.4</td>
<td>16.8</td>
<td>2</td>
<td>9.8</td>
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<tr>
<td>$\frac{\text{energy}}{\text{beam}}$ [MJ]</td>
<td>0.05</td>
<td>1</td>
<td>334</td>
<td>1320</td>
<td>3328</td>
<td>4200</td>
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<tr>
<td>$C$ [km]</td>
<td>6.9</td>
<td>6.28</td>
<td>26.7</td>
<td>26.7</td>
<td>233</td>
<td>233</td>
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<tr>
<td>$n_b$</td>
<td>6</td>
<td>36</td>
<td>2800</td>
<td>5600</td>
<td>40000</td>
<td>40000</td>
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<tr>
<td>$N_b \times 10^{11}$</td>
<td>1.7 ($p$)</td>
<td>2.7 ($p$)</td>
<td>1.05</td>
<td>1.05</td>
<td>0.26</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>0.8 ($\bar{p}$)</td>
<td>$\sim$ 1.0 ($\bar{p}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\hat{L}}{10^{34}\text{cm}^{-2}\text{s}^{-1}}$</td>
<td>0.0006</td>
<td>$\sim$ 0.02</td>
<td>1.00</td>
<td>10.</td>
<td>1.0</td>
<td>2.0</td>
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<tr>
<td>$\sigma_{x,y}^* \ [\mu \text{m}]$</td>
<td>80, 40</td>
<td>32</td>
<td>15.9</td>
<td>7.4*</td>
<td>4.6</td>
<td>3.4 → 0.79</td>
</tr>
<tr>
<td>$\sigma_{x',y'}^* \ [\mu \text{rad}]$</td>
<td>136, 272</td>
<td>91</td>
<td>31.7</td>
<td>34*</td>
<td>15</td>
<td>5 → 1</td>
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</tbody>
</table>

F. Zimmermann

Accelerator Physics Issues at the LHC and Beyond
<table>
<thead>
<tr>
<th>acc.</th>
<th>SppS</th>
<th>TeV2a</th>
<th>LHC</th>
<th>LHC-II</th>
<th>VLHC-I</th>
<th>VLHC-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{x,y}^* [m]$</td>
<td>0.6, 0.15</td>
<td>0.35</td>
<td>0.5</td>
<td>0.22</td>
<td>0.3</td>
<td>0.71</td>
</tr>
<tr>
<td>no. of IPs</td>
<td>3</td>
<td>2</td>
<td>2 (4)</td>
<td>2 (4)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>bb t.-s./IP $\xi_{x,y}$</td>
<td>0.005</td>
<td>0.01</td>
<td>0.0034</td>
<td>0.003→0.005</td>
<td>0.002</td>
<td>→0.008</td>
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<tr>
<td>$\theta_c [\mu\text{rad}]$</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>300</td>
<td>153</td>
<td>10</td>
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<tr>
<td>$\sigma_z [\text{cm}]$</td>
<td>30</td>
<td>37</td>
<td>7.7</td>
<td>4.0</td>
<td>3.0</td>
<td>→1.5</td>
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<tr>
<td>$L_{sep} [\text{m}]$</td>
<td>1150</td>
<td>119</td>
<td>7.48</td>
<td>3.74</td>
<td>5.645</td>
<td>5.645</td>
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<tr>
<td>$P_{SR} [\text{kW}]$</td>
<td>&lt; $10^{-3}$</td>
<td>3.6</td>
<td>114</td>
<td>7</td>
<td>1095</td>
<td></td>
</tr>
<tr>
<td>$dP/ds [\text{W/m}]$</td>
<td>$\ll 10^{-3}$</td>
<td>0.2</td>
<td>6.6</td>
<td>0.03</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{IBS}} [\text{hr}]$</td>
<td>10</td>
<td>50(?)</td>
<td>142</td>
<td>345 (in.)</td>
<td>400</td>
<td>4000→1</td>
</tr>
<tr>
<td>$\tau_{y,SR} [\text{hr}]$</td>
<td>1200</td>
<td>52</td>
<td>6.5</td>
<td>200</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>d.d./IP $\delta [10^{-10}]$</td>
<td>0.025</td>
<td>2.5</td>
<td>20</td>
<td>5</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>events/cross.</td>
<td>~6</td>
<td>18</td>
<td>90</td>
<td>21</td>
<td>54</td>
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<tr>
<td>acc.</td>
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<td>VLHC-II</td>
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<td>--------------</td>
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<td>--------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>lum. lifet. $\tau_L$ [hr]</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>3.2</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>tune $Q_\beta$</td>
<td>26</td>
<td>$\sim 20$</td>
<td>63</td>
<td>63</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>$\gamma \epsilon_{x,y}$ $[\mu m]$</td>
<td>3.75</td>
<td>$\sim 3$</td>
<td>3.75</td>
<td>3.75$\rightarrow1.0$</td>
<td>1.5</td>
<td>1.6$\rightarrow0.04$</td>
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<tr>
<td>$\gamma \epsilon_{x}^{eq}$ $[\mu m]$</td>
<td>$\sim 10^*$</td>
<td>2.03</td>
<td>1.07</td>
<td>1.0</td>
<td>0.06</td>
<td></td>
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<tr>
<td>$\epsilon_L$ ($\sigma$) $[eVs]$</td>
<td>0.11</td>
<td>0.11</td>
<td>0.2</td>
<td>$\rightarrow0.15$</td>
<td>0.4</td>
<td>0.4$\rightarrow0.1$</td>
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